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Space Technology 5 – A Successful Micro-Satellite Constellation Mission

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ABSTRACT

The Space Technology 5 (ST5) constellation of three micro-satellites was launched March 22, 2006. During the three-month flight demonstration phase, the ST5 team validated key technologies that will make future low-cost micro-sat constellations possible, demonstrated operability concepts for future micro-sat science constellation missions, and demonstrated the utility of a micro-satellite constellation to perform research-quality science. The ST5 mission was successfully completed in June 2006, demonstrating high-quality science and technology validation results.

MISSION OVERVIEW

The Space Technology 5 (ST5) Project is part of the National Aeronautics and Space Administration (NASA)'s New Millennium Program (NMP). NMP provides a bridge to mature new technology systems and components from initial concept to mission use by demonstrating them in space. ST5 is a constellation of three micro-satellites launched on a single Pegasus XL rocket on March 22, 2006. After operating successfully for its nominal 90-day mission, ST5 completed decommissioning on June 30, 2006. Goddard Space Flight Center (GSFC) is responsible for the ST5 mission.

Each ST5 spacecraft is ~25 kg in mass, and includes the following component/subsystem technologies:

- Miniature Transponder for space to ground communications
- Cold Gas Micro-Thruster for propulsion and attitude control
- Complementary Metal Oxide Semiconductor Ultra Low Power Radiation Technology (CULPRiT) chip used for Reed-Solomon encoding
- Low-voltage power subsystem, featuring
 - Lithium-Ion Battery
 - Triple-junction Solar Array
- Variable Emittance Coatings for dynamic thermal control
- Miniature Magnetometer

- Miniature Spinning Sun Sensor
- Magnetometer Deployment boom
- "Evolved" X-band Antenna
- Nutation Damper

The ST5 spacecraft were deployed into a "string of pearls" constellation with all three spacecraft in the same orbit plane, in a polar sun-synchronous orbit. The perigee was approximately 300 km, and the apogee was approximately 4500 km. In this orbit, the initial argument of perigee is approximately 160 degrees, and the orbit line of apsides (and therefore the position of the apogee over the Earth) precesses approximately 1.2 degrees per day into the southern hemisphere.

ST5 demonstrated concepts for the operational management of future constellation missions, such as automation, formation flying and ground communication strategies. These concepts will be useful for future missions that plan to operate multiple spacecraft with minimal ground support personnel.

ST5 demonstrated the utility of a constellation of micro-satellites to perform research-quality science. Using precision magnetometers, the ST5 spacecraft are able to detect and respond autonomously to science events, and to dynamically change data recording rates in response to significant changes in the magnetic field. Data from the three spacecraft were used to provide simultaneous, multi-point measurements of the magnetic field associated with the Earth's auroral region, as well as data on crustal magnetic fields.

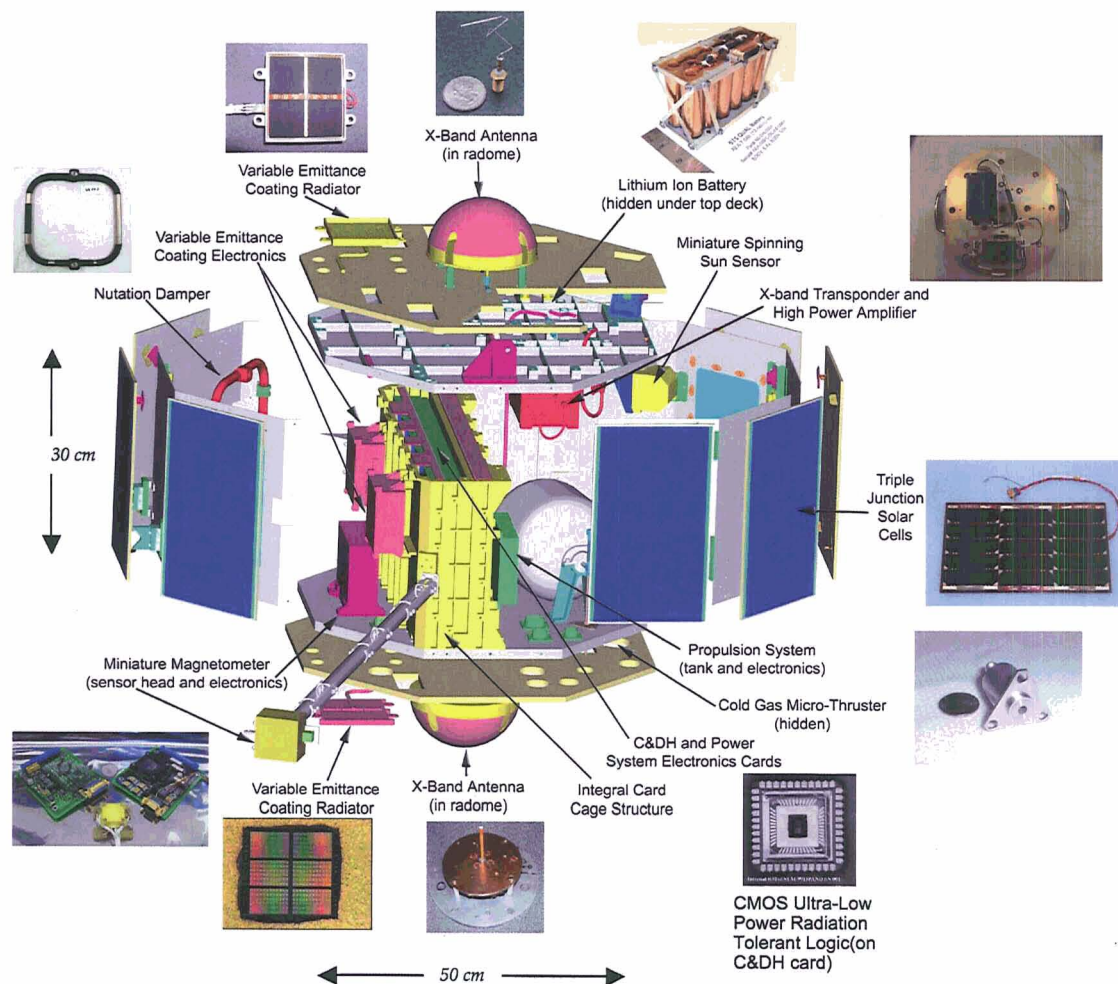


Figure 1: ST5 Spacecraft and Components

SPACECRAFT OVERVIEW

The ST5 spacecraft (Figure 1) is a very capable micro-satellite with the full subsystem functionality found in larger spacecraft. The spacecraft was built within tight volume ($<1 \text{ m}^3$) and mass constraints ($\sim 25 \text{ kg}$). Each ST5 spacecraft is octagonal in shape, approximately 25 kg in mass, and approximately 53 cm in diameter by 48 cm in height. The ST5 micro-satellite represents approximately a two to five-fold reduction in mass and volume over comparable spacecraft using flight-validated components. No “off-the-shelf” small spacecraft would meet ST5 requirements without substantial modification. The ST5 spacecraft is built to withstand the space radiation environment, thermal environment variations, and high launch loads required for future mission applications. The spacecraft power system is low-power and low-voltage, and is designed

to power up after separation from the launch vehicle. The spacecraft is spin stabilized with a passive nutation damper, simplifying attitude control. The spacecraft bus was developed “in-house” by GSFC. Academic and industry partners delivered some of the key technology components, as described below.

Miniature Transponder for Space to Ground Communications

The ST5 digital X-Band Transponder, built by AeroAstro Inc., provides all of the communication between the spacecraft and the ground. It is capable of command uplink at 1 kbps and telemetry downlink at 1 or 100 kbps, and enables coherent Radio Frequency (RF) Doppler tracking. It is a low mass ($\sim 870 \text{ g}$), low power system ($<5 \text{ W}$). In addition to the transponder, the ST5 RF communications subsystem includes a high

power amplifier (HPA) (1.5W RF output power), diplexer, band pass filter and two X-band antennas with 3dB splitter.

The ST5 transponders were used extensively throughout the mission. Commands were sent to the satellites, science and housekeeping telemetry data was received from the satellites, and Doppler tracking data was obtained and used to determine the orbits of the satellites. For ST5, the transponders were used with the NASA McMurdo Ground Network (GN) station and the three Deep Space Network (DSN) stations (Goldstone, Madrid, and Canberra).

The ST5 transponder could potentially be used with commercial or dedicated ground stations. It would be most useful to future constellation missions requiring small, low mass, and low power satellites in Low or Medium Earth Orbit (LEO or MEO.)

Cold Gas Micro-Thruster for Propulsion and Attitude Control

Each ST5 spacecraft propulsion system incorporates a single Cold Gas Micro-Thruster (CGMT) from Marotta Scientific Controls, Inc. The CGMT uses nitrogen gas as propellant, and features very low power draw and low leakage rates. It is capable of being operated in both pulse and continuous fire modes, and was used for both delta-V and attitude control. The latching solenoid valve design provides an order of magnitude reduction in power consumption compared to thrusters based on continuous duty solenoid valves. It is only 78g in mass, and is capable of 2.1N of thrust at 2000 psi, with a graceful degradation to 0.1N of thrust at 100 psi.

The cold gas micro-thruster is part of a welded propulsion system consisting of a propellant tank, pressure transducer, filter, fill and drain valve, and associated braces and tubing, and is controlled by thruster control electronics.

The micro-thrusters were used extensively on orbit to maneuver the spacecraft into the constellation formation. At the end of the mission, the propulsion tanks were completely emptied, allowing measurement of the thruster performance over the entire range of pressures. Two of the micro-thrusters were fired more than 6000 pulses, with final tank pressures of less than 30 psi.

The CGMT technology is useful to any future missions needing a small, lightweight and low power thruster. The propulsion tank, pressure transducer and pressure transducer electronics could also be applicable to future missions.

Complementary Metal Oxide Semiconductor Ultra Low Power Radiation Technology (CULPRiT) Chip

CULPRiT is a Complementary Metal Oxide Semiconductor (CMOS) Radiation Tolerant technology that allows circuits to operate at low voltage. The technology is capable of significant power reduction over current technology, while achieving radiation and latch-up tolerance. For ST5, the CULPRiT chip operates at 0.5V, and is used as a Reed Solomon Encoder. CULPRiT partners included the Center for Advanced Microelectronics and Biomolecular Research at the University of Idaho, AMI Semiconductor and PicoDyne Inc.

Prior to flight, CULPRiT chips were subjected to Single Event Upset testing at Brookhaven National Laboratory and Total Dose testing at GSFC. The CULPRiT technology was radiation tolerant to a total dose of over 200 krad. In addition, there was no latch-up observed out to effective LET values in excess of 90 MeV-cm²/mg.

CULPRiT performed exceptionally well over the ST5 mission. Approximately 330 million telemetry frames were sent through the CULPRiT technology Reed-Solomon Encoder without a single bit error, while over 10,000 radiation events affected the dynamic random access memory on the three spacecraft during the course of the mission.

For future missions, CULPRiT logic could be applied in many areas of spacecraft avionics design, either as-is or extending the development to a lower operating voltage, smaller feature size and greater total dose hardness.

Low-Voltage Power Subsystem, Featuring Lithium-Ion Battery and Triple-Junction Solar Cells

The Electrical Power Subsystem of the ST5 spacecraft provides electrical services to all components and subsystems on the spacecraft. A single double-sided Power System Electronics card provides power conditioning for three separate service types: Unregulated battery-bus, Regulated 5.25V bus and Regulated 5.0V Command and Data Handling (C&DH) Supply.

ST5 used a Lithium-Ion battery during periods of high power consumption or eclipse. Lithium-Ion provides a dramatic three-fold improvement in energy density over existing batteries. The ST5 battery contains internal over-charge, over-temperature and over-pressure protection. It is low volume (12.7cm x 6.5cm x 8.6cm) and low mass (645g). It provides total usable energy storage of 9 A-h (beginning of life) at the maximum

operating voltage of 8.4V. The ST5 battery was provided by ABSL.

The ST5 solar array is composed of 8 body-mounted panels with a total power-generating capacity of 25W (beginning of life) at approximately 10V. The Solar Array is constructed of a composite facesheet substrate, triple-junction cells, cover glass, and associated wiring and interconnects. The graphite composite solar panel substrates are only 86 grams each. The solar arrays are constructed using a low magnetic signature back-wiring mesh. At procurement time, the triple junction ST5 solar cells were the highest efficiency available in the U.S., and were available only as research quality cells. The raw cell efficiencies vary from 28.1 to 29.1 percent at 1 sun intensity (without the added complexity of solar concentrators). In comparison, the standard production dual junction cells on the Microwave Anisotropy Probe (MAP) spacecraft, launched in 2001, were 18 percent efficient at 1 sun. The ST5 Project partnered with the Air Force Research Lab to procure and test the ST5 solar cells, which were provided by Emcore.

The performance of the low voltage power system on the three ST5 spacecraft was better than predicted. The solar arrays generated more power than the model results due to additional illumination from Earth albedo. The batteries had sufficient capacity to perform all required functions and demonstrated minimal capacity fade and quick battery voltage recovery. The ST5 low voltage power system demonstrates that a miniature, but full performance power system is achievable.

The ST5 battery and solar array are useful to future missions as-is, or could be easily scaled up or down.

Variable Emittance Coatings for Dynamic Thermal Control

Two variable emittance coatings (VEC) technologies were demonstrated on ST5. The technologies were not an integral part of the overall thermal-control system, but were flown as "stand-alone experiments," isolated from the spacecraft and equipped with calibration heaters.

The Micro Electro-Mechanical Systems (MEMS) VEC radiator was developed by the Applied Physics Laboratory (APL), using shutters provided by Sandia National Laboratories. The shutters are manufactured from a multi-layered silicon chip process called SUMMiT V. The effective emittance is modulated by varying the total number of arrays that are open or closed.

The Electro Static Radiator (ESR) VEC radiator was developed by Sensortex, Inc. It consists of a thin film made of a composite metalized polymer. The polymer operates as a thermal switch to change between radiative or conductive heat transport, thereby effectively varying the emissivity of the surface. The thermal switching is controlled via electrostatic forces from an applied direct-current voltage.

Intelligent thermal control through variable emittance systems would be most useful to small spacecraft applications where large thermal fluctuations are expected due to the small thermal mass and limited heater power. The ST5 VECs serve as a proof-of-concept, despite some problems that they experienced, with further development required for future missions.

Miniature Magnetometer

The University of California at Los Angeles ST5 Magnetometer is a low power, 3-axis fluxgate, research-grade vector magnetometer system, designed to provide attitude determination and characterize vehicle dynamics. The magnetometer sensor head is only 55g in mass, and 5cm x 5cm x 3cm in volume. It has a dynamic range of +/-64,000 nT in low sensitivity/full range and +/-16,000 nT in high sensitivity/low range.

The ST5 science validation team confirmed magnetometer data accuracies of 0.1 degrees in pointing knowledge and 0.1 percent in field strength at perigee. Magnetic signatures of science-events as small as a few nT can be readily identified in the data with a background field up to ~50,000 nT. Using these precision magnetometers, the ST5 data revealed information not only on targeted auroral field-aligned currents, but also on the Earth's crustal magnetic field.

The ST5 magnetometer is useful for any spacecraft requiring a very capable miniature magnetometer.

Miniature Spinning Sun Sensor

The Adcole Corporation Miniature Spinning Sun Sensor (MSSS) consists of a two-reticle spinning sun sensor and processing electronics packaged in one unit. The data from the MSSS is used in support of ground-based spacecraft attitude determination.

On orbit, the ST5 MSSS produced multiple Sun pulses per spin period, due to a non-commandable threshold circuit in the hardware. The Sun sensor vendor, Adcole Corporation, was able to recreate the spurious pulse effect with an engineering test unit. The ST5 team was able to work around this via flight software mitigation and operationally constraining attitude maneuvers to an acceptable range of slew angles.

The Adcole miniature sun sensor is applicable to a wide range of future missions. An improved electronics and baffle design has now been demonstrated on the THEMIS spacecraft, and does not exhibit the multiple sun pulses that the ST5 Sun sensor does.

Magnetometer Deployment Boom

The ST5 magnetometer boom is constructed as an assembly of graphite composite tube sections with three segments of beryllium copper "carpenter tape" hinges. It is 225g in mass and 80 cm in length. It was designed to minimize magnetic interference with the magnetometer, provide thermal and dynamic stability, and hold the magnetometer in a constant position with respect to the spacecraft axes.

The boom is stowed around three sides of the octagonal spacecraft for launch. It is held in place with a low-shock shape memory alloy activated pin puller, developed by TiNi. The strain energy developed as the boom is stowed is used to deploy the boom on orbit. The boom deploys on command from the ground and protrudes from one vertex of the spacecraft. The magnetometer is held about 1.5 spacecraft diameters from the central body in order to reduce the effects of any stray magnetic fields from within the body of the spacecraft.

All three ST5 magnetometer booms deployed nominally, based on spacecraft telemetry. The magnetometer data was very stable, indicating that there was no fluctuation in the magnetometers' position with respect to the spacecraft.

If used on other launch vehicles with higher mechanical environments than the Pegasus, the boom tie-down mechanisms will likely need some amount of re-design. Otherwise, the boom could be used as-is, or the design extended for future small satellite applications.

Nutation Damper

Each of the three ST5 spacecraft contains a passive nutation damper, designed by GSFC. The dampers are in a form of a ring-shape titanium tube that is 19.5cm x 19.5cm, with a diameter of 1.27 cm. The dampers are fully filled with silicone, and there is no bellows. The dampers have a Maximum Expected Operation Pressure (MEOP) of 10,000 psi.

The ST5 nutation dampers successfully damped the nutation inducted from the spacecraft deployments, magnetometer boom deployments, and all maneuvers. The on-orbit performance results verified that the damper time constants were less than 60 minutes, and steady-state nutation angles were less than 0.5 degrees.

The on-orbit performance correlated with ground testing results.

The nutation damper could be used as-is for future missions.

"Evolved" X-band Antenna

Each ST5 spacecraft has 2 antennas -- one each on the top and bottom decks in order to give nearly 4π steradian coverage. The south-facing antenna is a quadrifilar helix antenna with a beam shape that was developed for the equatorial Geosynchronous Transfer Orbit (GTO) originally planned for ST5. It is attached to a ground plane that contains an internal matching network. The north-facing antenna is an "evolved" antenna designed using a computer program based on a "genetic" algorithm. The algorithm designs a wire form radiator, "evolving" the design based on a "fitness function" computed from voltage standing wave ratio and gain scores. The ST5 evolved antenna was designed to maximize the gain towards zenith to accommodate the GN McMurdo station. The evolved antenna design has the potential for high gain across a wider range of elevation angles and more uniform coverage (a very uniform pattern over the 40-90 degree elevation angles of greatest interest).

The evolved antenna had several advantages over the quadrifilar helix antenna, including better coverage, significantly higher efficiency, as well as easier and more reliable construction. Most significantly, rapid redesign was accomplished at a small cost and in a short time frame when the planned ST5 orbit changed from GTO to polar LEO.

The evolved antennas were the first evolved hardware flown in space. They were used extensively throughout the mission, and performed very well. The design and manufacturing concepts for the ST5 evolved antennas could be extended to future missions.

DEVELOPMENT AND TEST APPROACH

Because ST5 was intended to be a pathfinder for future constellation missions of tens to hundreds of small satellites, the spacecraft were designed to be as simple as possible, while providing functionality found in larger spacecraft. The ST5 spacecraft are single string. They are passively spin-stabilized and have no onboard navigation or active attitude control (except in certain failure detection/correction scenarios), minimizing both development and operations cost. The ST5 spacecraft also have passive thermal control and nutation damping.

In order to optimize the cost vs. reliability of the spacecraft, an emphasis was placed on parts selection.

If cost-effective and readily available, the highest reliability parts (i.e., Grade 1 Class S or V) parts were used. Otherwise, Grade 2 parts were used for critical subsystems, and Grade 3 and commercial parts were used in less critical areas. Screening and radiation testing were performed on selected parts.

The ST5 design team was careful to meet spacecraft-induced magnetic field requirements. All materials and parts were constrained to be non-magnetic. For example, titanium and brass fasteners were used in the boom to minimize magnetic interference. The solar arrays were constructed using a low magnetic signature back-wiring mesh. The Lithium-Ion battery was shielded with Metglas. The magnetometer boom hinges were gold-plated to reduce thermal gradients that could potentially lead to small electrical currents and magnetic contamination.

To simplify integration and test (I&T), the ST5 top deck is removable, allowing access to all components. An integral card-cage provides the structural backbone of the spacecraft, as well as housing the C&DH and Power System Electronics cards. The various components are attached to either one of the two decks or the integral card-cage itself.

For critical or long-lead items, the ST5 sparing philosophy was to buy enough parts for four spacecraft, plus some additional spares. A fourth flight unit was built for the most critical items, such as the C&DH, card cage structure, power system electronics, sun sensor, magnetometer and transponder.

ST5 used a full qualification and acceptance test program for all components and the spacecraft. Components were delivered to spacecraft I&T fully qualified. Following qualification, components and subsystems were delivered to spacecraft system-level I&T, where they were integrated onto the spacecraft. Spacecraft 1 was integrated and tested first followed by spacecraft 2 and 3 simultaneously. Spacecraft-level environmental testing consisted of electromagnetic interference, electromagnetic compatibility, random vibration, shock, thermal-vacuum/thermal-balance, mass properties, and magnetics.

Magnetic cleanliness processes and procedures were used during spacecraft I&T. This included the use of non-magnetic tools when available, wooden benches, and the periodic degaussing of tools. Additionally, each component, prior to delivery to I&T, was degaussed and had its magnetic signature recorded at the GSFC Magnetics Facility during component level qualification.

I&T and Mission Operations personnel conducted system-level verification. A “test as you fly” approach, using scripts and procedures that transferred from I&T to Mission Operations, was used as much as possible. The Mission Operations Center and I&T teams used the same ground system for testing. Mission Readiness simulations, which simulated nominal operations and mission events, verified the spacecraft, ground system, and operations from end-to-end.

MISSION OPERATIONS

The ST5 spacecraft and ground system provide evolvable steps along the road to future constellation missions. The spacecraft have a high degree of simplicity and autonomy, and the ground system has a high degree of automation.

ST5 ground operations were automated through the use of several new technology components: Advanced Mission Planning and Scheduling (AMPS) system is a multi-satellite planning and scheduling system; Criteria Action Table/Advanced Network Services Registry (CAT/ANSR) is a paging system that monitors telemetry and alerts the Flight Operations Team (FOT) if needed; a SimulinkST5 model is used for memory/downlink and power management. To minimize the development cost of the ground system, the GSFC Mission Services Evolution Center (GMSEC) architecture was used to allow “plug and play” of ground system components. The GMSEC architecture features “socket” specifications and generic messaging between components.

On orbit, the spacecraft are stable and power positive without ground intervention for weeks at a time. The spacecraft are capable of monitoring and correcting for excessive thruster firing, transponder interface problems, C&DH system hang-ups, low battery or voltage conditions, and excessive sun angle.

The ST5 FOT was small, and the staffing level was intentionally reduced over the course of the mission to demonstrate low-cost constellation operations. There was a high reliance on automation from early in the mission. Near the end of the mission, we conducted one week of “lights out” operations. This test was conducted June 12-18, 2006. All routine and periodic functions were performed autonomously by the ground data system during this period. Operations personnel supported in a true “lights out” manner, providing off-line engineering support during the weekday day shift only and responding to alert notifications. In addition, an autonomous orbit maneuver was performed near the end of the mission. While a full complement of support personnel were present in the control center to support

the maneuver, all commanding was performed autonomously.

The three ST5 spacecraft were maneuvered into a “formation flying” configuration with separations of tens of kilometers to several hundred kilometers, via ground-controlled maneuvers. This “string of pearls” constellation formation enabled the mission science validation demonstration. The constellation formation was designed so that two or more spacecraft would be within a current sheet of the Earth’s aurora (the thickness of the auroral current sheet is typically approximately 500–1000 km).

MISSION RESULTS

The ST5 mission demonstrated the utility of a constellation of small satellites for scientific research. ST5 provided the first simultaneous, multi-point measurements of the magnetic field associated with the auroral current sheet^{1,2}. The ST5 spacecraft also observed lithospheric magnetic fields, also known as crustal magnetic fields, from the magnetization of Earth’s crust or magnetic minerals. ST5 observed a new class of magnetic pulsations that have never been reported before^{1,2}.

ST5 successfully addressed technology challenges for future micro-satellite missions, as well as development, test and constellation operations strategies. By validating miniaturized spacecraft and component technologies and constellation operations concepts in flight, ST5 enables future missions to use these technologies and concepts at reduced risk.

ST5 technologies are already being used by missions under development as well as included in proposals for future missions. Examples include the lithium-ion battery, miniature magnetometer, magnetometer boom, and ground system automation components. Infusion of various ST5 components and technologies enables any space mission to reduce overall mass, volume, power, cost and risk.

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References

1. Carlisle, C. and G. Le, “Space Technology 5 Technology Validation Results,” Proceedings of 2007 NASA Science Technology Conference, College Park, MD, June 2007.
2. Le, G., T. Moore and J. Slavin, “Space Technology 5—Enabling Future Constellation Missions Using Micro-Satellites for Space Weather,” Proceedings of 21st Annual AIAA/USU Conference on Small Satellites, Logan, UT, August 2007.
3. Carlisle, C., E. Webb, et al., ST5 Project Technology Validation Report, New Millennium Program document ST5-495-586 (export-controlled document available to U.S. persons who sign a Non-Disclosure Agreement).